Detection of Stator Short Circuit Faults in Three-Phase Induction Motors Using Motor Current Zero Crossing Instants

Abhisek Ukil, Shuo Chen, Andrea Andenna

Abstract-- Stator faults typically have a significant share amongst the common type of faults in industrial three-phase induction (asynchronous) motors. This paper presents a motor current signature analysis (MCSA)-based diagnostics of the stator winding short circuit fault. This type of fault happens due to the destruction of the turn insulation, and can be very detrimental causing motor shutdown. Instead of traditional MCSA using the motor stator current, in this paper, analysis using the zero crossing time (ZCT) signal of the stator current is presented. The theoretical aspects of the stator short circuit detection are presented. Following that, a diagnostic algorithm utilizing the ZCT signals is proposed. Experiments are performed with real motors, healthy and with shorted stator windings. Frequency analysis of the ZCT signals from the experimental data substantiates the theoretical arguments with significant accuracy.

Keywords— asynchronous motor, fault diagnosis, induction motor, insulation problem, MCSA, motor current, stator short circuit, stator winding fault, zero crossing time, ZCT signal.

I. INTRODUCTION

Three-phase induction (asynchronous) motors are industrial work-horses, responsible for consumption of 40 to 50% of generated electrical power [1–3]. Therefore, the diagnostics of induction motor problems are of prime importance. There are different kinds of induction motor faults, broadly classified as rotor and stator faults [2]. The source of such faults could be external and/or internal due to various electrical, environmental, mechanical reasons [2]. Diagnostics of induction motor faults using the motor current signature analysis (MCSA) [1–4] has been widely applied in the industry. MCSA is a noninvasive, online technique for the diagnosis of induction motor problems.

In this paper, we focus on stator short circuit fault in the industrial induction motor. Stator faults typically have a significant share of about 38% [3] amongst the common type of faults in industrial induction motors. Therefore, it is very important to detect such faults.

We present a diagnostic function for the online detection of the stator short circuit fault using MCSA. However, for the MCSA, we do not use the motor stator current, as is done normally. Instead, we use the zero crossing time (ZCT) signal of the stator current. This is an alternative approach, and particularly helpful in terms of reduced computational requirements due to less number of data points. Also, if explicit current measurement is unavailable, this can be an effective alternative approach, as will be demonstrated in the paper. Besides, utilization of the ZCT signal...
does not require any additional sensor than normal current sensors which are typically present in industrial motor/drives application setup.

The remainder of the paper is organized as follows. In section II, background information of this research work is presented. This include discussions on the stator short circuit fault, theory of detection of such fault with previous works and the concept of utilization of the ZCT signal for motor diagnostics. The detection algorithm using the ZCT signal is explained in details in section III. Section IV presents the experimental results, associated discussions validating the proposed diagnostic algorithm along with information on possible future directions. This is followed by conclusions in section V.

II. BACKGROUND INFORMATION

A. Stator Short Circuit Fault

Shorted turns in stator windings often do not affect the normal operation in the early stage. However, eventually that can grow into serious motor failure. In normal operation of industrial motors, there is usually 10 to 100V (AC) between the adjacent turns in a coil. The insulation is about 0.5mm thick as the voltage across the turn insulation is relatively low. However, substantial transient voltages across the turn insulation are possible during switching operations [9]. Majority of motor stator winding failure happens due to the destruction of the turn insulation caused by the short circuit in stator windings. The type of shorts could be of the following types [3]:

i. Inter-turn shorts of same phase
ii. Short between coils of same phase
iii. Short between two phases
iv. Short between phase to earth.

Fig. 1 shows the schematic diagram of the different types of stator winding problems except open-circuit of the stator coil which is out of scope of this paper. Several studies [5, 6, 9, 10, 11, 12, 19, 20] report that depending on the type of shorts, and condition of motor (age, working condition, etc), the motor may continue to operate initially, even though short-circuit current will flow, causing more and more overheating, ultimately leading to complete failure if not accounted for. The studies [5, 6, 9, 10, 11, 12, 19, 20] also point that with the inter-turn and coil short of same phase, the motor might still continue to run. The detrimental ones are the short between the phases and phase-to-earth, causing instantaneous motor shutdown. About the failure mode trend, it is generally argued that the shorts in a particular phase, if undetected, would grow onto phase-to-phase faults. Although there are no exclusive data to indicate the transition time between inter-turn (in same phase) and groundwall (between phase-to-phase) insulation failure [10], however, detection of inter-turn shorts during motor operation would reduce the damage to adjacent coils and the stator core, reducing repair cost and motor outage time.

B. Detection of Stator Short Circuit

A lot of studies have been performed associated with turn insulation breakdown, studying the long term degradation of insulation [5–6], effects of voltage surges [7], partial discharges [8] etc. Literature reviews on various aspects of stator winding failures are reported in [11, 19, 20]. In the current paper, we concentrate on the current components in the stator winding that are only a function of shorted turns and are not due to any other problem or mechanical drive characteristic.
The occurrence of a fault on the motor results in a change in the air gap space harmonic distribution. These space harmonics cannot be detected directly by a search coil [9]. However, the search coil can detect the time harmonics of the axial flux. Thus it is necessary to derive the relationship between the space and time harmonics in order to correctly interpret the frequency spectrum obtained from the search coil(s) [9–10].

The space harmonic distribution of magnetomotive force (mmf) due to a balanced, full pitched, three phase winding fed from a balanced supply frequency, \( \omega \), is given by

\[
m = 0.955N_1 \left[ k_{w1} \cos(\omega t - p \theta) + 0.2k_{w5} \cos(\omega t + 5p \theta) \\
-0.14k_{w7} \cos(\omega t - 7p \theta) + 0.09k_{w11} \cos(\omega t + 11p \theta) - \ldots \right]
\]

where \( k_{wn} \), is the n-th winding factor, \( p \) is the number of pole pairs, \( \theta \) is the angular displacement from the stator datum [9]. This represents a rotating set of harmonics of order \((6n \pm 1)\), which can be simplified to the corresponding air gap fluxes,

\[
B_n = B_{1n} \cos(\omega t - p \theta) + B_{5n} \cos(\omega t + 5p \theta) - B_{7n} \cos(\omega t - 7p \theta) + B_{11n} \cos(\omega t + 11p \theta) - \ldots
\]

where \( B_{kn} \), are the spatial harmonic fluxes [9].

This expression is in the stator frame of reference. Consequently, because the shaft flux of the rotor is of interest, it is necessary to refer (2) to the rotor reference frame. Consider the situation in which \( \beta \) is the angular displacement between the rotor and stator datum positions, and \( \alpha \) is defined to be the angular displacement from the rotor datum. Then \( \theta = \alpha + \beta \) [9].

If the angular rotor speed is \( \omega_r \), then,

\[
\theta = \alpha + \omega_r t,
\]

Now, using the normal expression for the slip of the motor, i.e. \( s = (\omega_s - \omega_r) / \omega_s \), where \( \omega_s \) the synchronous speed, = \( \omega / p \), and

\[
\omega_r = \omega(1 - s) / p.
\]

Now, the general term of (2) is,

\[
B_{kn} = B_{kn} \cos(\omega t \pm np \theta).
\]

Substituting this in (3) & (4) leads to,
\[ B_{ns} = B_n \cos[(1 \pm n(1-s)\omega t \pm n\alpha)]. \]  

Equation (6) gives the frequency components of the currents that are induced in the rotor due to the air gap space harmonics of a balanced winding and supply. In addition to these harmonics, the fundamental of the supply frequency will also appear in the axial flux spectrum.

The effect of the interturn fault is to remove a turn from the stator winding. This will have a small, but finite, effect on the main air gap flux distribution. In addition, an electromotive force (emf) will be induced in the shorted turn which will result in a current flow limited only by the self impedance of the fault. This impedance essentially determines the transition time between turn and groundwall insulation failure [9–10].

The fault current due to the shorted turn is the source of an additional mmf pulse, which also has a space harmonic distribution which is superposed on the main field distribution. From previous considerations, it follows that this will lead to a change in the time harmonics observed in the leakage field. These effects form the basis of the fault identification technique. The changes expected can also be predicted mathematically.

Fourier analysis of the mmf waveform shows that it contains all harmonics except the fourths [9–11], i.e.,

\[ B_s = 0.5 \sum B_n \cos(\omega t \pm n\theta), \quad n \neq 4m, \quad \text{all } m. \]  

For the general case, the corresponding waveform would have a mark-space ratio of 1: \((2p-1)\) causing every \(2p\)-th harmonic to be absent. Hence the time harmonics produced by the rotor are given by,

\[ B_s = 0.5 \sum B_n \cos[(1 \pm n(1-s)/p)\omega t \pm n\alpha], \quad n \neq 2pm, \quad \text{all } m. \]  

Adding in supply time harmonics of higher order \(k\), leads to the completely general expression, expressing the components in the airgap flux waveform as a function of shorted turns [3].

\[ f_{\text{short}} = f_i \left[ k \pm \frac{n}{p} (1-s) \right], \]  

where,

- \(f_{\text{short}}\) is the frequency component that is a function of shorted turns
- \(f_i\) is the supply frequency
- \(p\) is the number of pole pairs
- \(s\) is the slip,
- \(n\) and \(k\) are two parameters, such that \(n = 1, 2, 3, \ldots\), and \(k = 1, 3, 5, \ldots\)

By putting \(k = 1\) in (9), we can see that the following frequency component \(f_{\text{comp}}\) would be induced in the spectrum of the stator current, superposed on the fundamental current,

\[ f_{\text{comp}} = f_i \left[ \frac{n}{p} (1-s) \right], \]  

where, \(n = 1, 2, 3, \ldots\). This component is visible in the frequency spectrum of the stator current (as side-band to the fundamental peak). This will affect the normal ZCT spacing, causing the indicative frequency components to appear at locations given by (10) in the spectrum of the ZCT signal as well. Since this stator fault component in the ZCT spectrum is independent of motor inertia, it can be used as a good indicator of the stator short circuit fault. However, putting \(n = 1\) in (10) we would get
Equation (11) is the relationship for the rotor frequency. Therefore, for \( n = 1 \), we would not be able to distinguish the frequency peak due to stator fault as we will always have an identical peak due to rotor frequency in the ZCT spectrum. Therefore, we have to utilize value of \( n > 1 \).

C. Application of ZCT Signal for Motor Diagnostics

Since 1980s MCSA has been applied for induction motor condition monitoring. In recent times, monitoring of the fluctuations in the motor current zero crossing instants in the frequency domain are used for motor diagnostics as well.

The ZCT signal is defined as the time difference, usually in milliseconds, between two successive zero crossing points of the stator phase current stored as a data file. This is given by the equation:

\[
T_{ZC}(n) = T(n+1) - T(n),
\]

(12)

where, \( T_{ZC} \) is the ZCT signal data, \( T(n) \) is the time of the \( n \)-th ZCT of the current signal, \( n = 1, 2, \ldots, N \) is the data index and \( N \) is the total number of samples available.

In a symmetrical induction motor, the time interval between two successive ZC points of the stator current is constant, referring as the natural reference of the ZCT. In a 50 Hz supply system, if the ZCT signal is taken from a single phase stator current, this time interval is 10 ms, giving a sampling frequency of 100 Hz and a frequency range of 50 Hz for the ZCT signal spectrum. If the ZCT signal is taken from three-phase stator current, this time interval is 3.333 ms, giving a sampling frequency of 300 Hz and a frequency range of 150 Hz for the ZCT signal spectrum. In practice, the mean, which is the natural reference, is always subtracted to ease the complexity of computation. Then, (12) is modified as:

\[
T_{ZC}^{\text{ref}}(n) = T(n+1) - T(n) - T_{\text{ref}},
\]

(13)

where, \( T_{\text{ref}} \) is the natural reference time of the ZCT signal.

The following advantages can be gained by using ZCT signal for motor diagnostics purposes.

i. The number of points in the signal would be much less than the stator current signal which is normally used in the MCSA. Therefore, the frequency computation and other data-driven computational burden would be much smaller. Sample storage requirement would be also much smaller.

ii. These would be particularly helpful for smaller embedded devices which often come with limited computational resources, e.g., without digital signal processors (DSPs) or high-end microcontrollers on-board, limited amount of storage, etc.

iii. There will be no need to employ additional sensors other than normal current sensors which are typically already in place in many motor applications.

iv. Often for smaller devices, there might not be explicit three-phase stator current measurement system on-board. Depending on the function of the device, there might be rectified current, partial measurement like peak current measurement only, etc. Frequency analysis of these types of currents does not help diagnostics because they do not reveal all the components, introduces additional harmonic components etc. In those cases, ZCT measurement could be easily implemented to directly measure the ZCT signal as a square wave toggling between \(+A\) and \(–A\) (where \(A\) is some gain parameter). Such ZCT signals could then be equally useful for motor diagnostics, etc.
v. There would be no need for high sampling rate in the electronics.

vi. The ZCT signal would reveal the same diagnostics information.

The spacing between successive ZCT would be unequal due to motor abnormalities. This is because due to the motor disturbances like broken bar, stator short circuits, bearing faults, there would be additional components in the stator current, affecting the normal ZCT spacing. Using this property, ZCT signals have been applied for broken rotor bar detection, as reported in [13–16]. For example, the ZCT spectral component at $2sf_1$ ($f_1$ is the supply frequency, $s$ is the slip) would be influenced by the existence of the broken rotor bars. And this is utilized to detect the broken rotor bars [15–16]. Application of the ZCT signal for rotor frequency estimation can be found in [13–14]. Online MCSA for stator short circuit faults has much interest as cited in [12]. In this paper, we would concentrate on the online detection of the stator short circuit faults using the frequency spectrum of the ZCT signal instead of the stator current signal.

III. DETECTION ALGORITHM

A. Acquisition of ZCT Signal

The ZCT signal to be used for the detection of the stator short circuit can be directly measured alongside the current measurement. Usually, that would be a square wave toggling between $+A$ and $-A$ (where $A$ is some gain parameter). However, if such electronics does not exist, it could be easily calculated from the measured motor current. This is explained below.

Fig. 2 depicts the algorithm for calculating the ZCTs of a single phase stator current. In Fig. 2, A and B are two successive phase current data points with opposite signs. Therefore, they are assumed to be the $n$-th and the $(n+1)$-th data points, and there is one and only one ZC point falling in between them. The time at which A and B are sampled are $t(n)$ and $t(n+1)$, respectively. The values of the current at A and B points are $y_a$ and $y_b$, respectively. $Z$ is the $k$-th ZC point at time $T(k)$. Having the above definitions in mind, the following relationships can be yielded, assuming approximately linear segment between the points A and B,

$$\frac{y_a - 0}{y_a - y_b} = \frac{t(n) - T(k)}{t(n) - t(n+1)}.$$  \hspace{1cm} (14)

Then, the time of the $k$-th ZC point may be calculated as:

$$T(k) = t(n) + \frac{y_a [t(n+1) - t(n)]}{y_a - y_b}.$$  \hspace{1cm} (15)

where, $t(n+1) - t(n)$ is the sampling interval whose value is the reciprocal of the sampling frequency. In the end, the ZC signal is yielded by applying (13). If three-phase ZC signals are needed, the ZC signal of each phase should be calculated as the first step, and then simply superposed together with respect to the time index.

It is to be noted that, for direct ZCT signal measurement using hardware, often comparators are used. These comparators check if the sample value is more than a positive threshold (e.g., point B in Fig. 2) or less than a negative one (e.g., point A in Fig. 2), and accordingly it holds the zero-crossing signal (for positive or negative halves) or toggles it. In order to account for physical limitations, noise, etc, these thresholds are usually not set at exactly zero, but little above and below zero. Thus, the sinusoidal waveform (e.g., top plot of Fig. 2) gets transformed into a ZCT signal of square wave shape, but linear interpolation would be required to improve the accuracy.
B. Diagnostics Algorithm

The algorithm of detecting the stator short circuit using the ZCT signal is depicted by the flowchart in Fig. 3. In the algorithm, first the ZCT signal is acquired either by direct measurement (if such electronics exist) or by calculating from the measured stator current as discussed in section III.A. Then, the frequency spectrum of the ZCT signal is calculated by using the discrete Fourier transform (DFT) [17]. This can be achieved by using the fast Fourier transform (FFT) [17] algorithm. Following that, the search for the stator short circuit indicative frequency peaks in the frequency spectrum of the ZCT signal is performed. These frequency components are given by (10), with the parameter \( n > 1 \), as \( n = 1 \) would indicate the rotor speed peak. Existence of such frequency peaks would confirm the existence of stator short circuit fault. Application results of this algorithm are presented in the following section.

IV. APPLICATION RESULTS

A. Experimental Setup

For verifying the proposed stator short circuit diagnostics, laboratory tests were performed to acquire current samples at 10 kHz sampling frequency using the setup shown in Fig. 4-a. Two identical motors of type SZJKe were used for the tests. Stator windings of one of the motors were taken out and 50% of the windings were short circuited, while the other one was healthy. The motor stator windings are random wound, i.e., without any slots, as shown in Fig. 4-b. Therefore, 50% short does not mean 50% of the total number of coils were shorted. Instead, 50% indicates that the voltage across the shorted coils attain 50% of the per phase voltage. This could happen to coils next to each other. Because in a random wound winding (see Fig. 4-b), coils which physically appear next to each other, might be electrically apart, hence having a higher resistance and causing higher voltage drop. So, if one coil has inter-turn short or two coils of same phase get shorted, for a typical 50 turns/phase winding, this means 2% and 4% of the windings are shorted. It is effective to represent the short in terms of % of per phase voltage, because the voltage is
important for the insulation withstand capability. Also, the voltage can be easily measured using a voltmeter, compared to physical inspection of short circuit inside the winding and expressing as % of number of turns.

Tables I–III show the specifications of the two same type motors used (one healthy, one with shorted stator winding). Table I describes the ratings of the motors, directly used for the signal analysis described later. Tables II–III are not directly used for the analysis of stator short described in the scope of this paper. Table II shows the equivalent circuit parameters, which would require short-circuit and no-load tests, not readily available from the Internet, etc. Hence, any analysis using the equivalent circuit parameters, internal motor parameters (e.g., to monitor changes in stator resistance as function of shorting, etc) could make use of it. Table III shows bearing related information, which is also of interest for the motor community [1–2].

![Flowchart of the stator short circuit detection algorithm using the ZCT signal.](image)

Fig. 3. Flowchart of the stator short circuit detection algorithm using the ZCT signal.
Fig. 4. (a) The laboratory setup for induction motor stator short circuit experiments, (b) the random wound stator winding of the motor types used in the experiments.

### TABLE I: RATINGS OF MOTOR SZJKe

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active power $P_N$ [kW]</td>
<td>0.8</td>
</tr>
<tr>
<td>Nominal voltage $U_N$ [V]</td>
<td>380</td>
</tr>
<tr>
<td>Nominal current [A]</td>
<td>2.2</td>
</tr>
<tr>
<td>Nominal power factor $\cos\varphi_N$ [-]</td>
<td>0.74</td>
</tr>
<tr>
<td>Rotor speed [rpm]</td>
<td>1400</td>
</tr>
<tr>
<td>No load speed [rpm]</td>
<td>1497</td>
</tr>
<tr>
<td>Winding connection</td>
<td>Y</td>
</tr>
<tr>
<td>Number of poles per phase winding $p$ [-]</td>
<td>2</td>
</tr>
<tr>
<td>Nominal frequency [Hz]</td>
<td>50</td>
</tr>
<tr>
<td>Number of rotor bars [-]</td>
<td>22</td>
</tr>
<tr>
<td>Rotor inertia [kg*m^2]</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

### TABLE II: EQUIVALENT CIRCUIT PARAMETERS OF MOTOR SZJKe

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator winding resistance $R_s$ [Ohms]</td>
<td>8.4</td>
</tr>
<tr>
<td>Referred rotor winding resistance $R_s'$ [Ohms]</td>
<td>8.2</td>
</tr>
<tr>
<td>Stator winding reactance $X_s$ [Ohms]</td>
<td>10.3</td>
</tr>
<tr>
<td>Referred rotor winding reactance $X_s'$ [Ohms]</td>
<td>10.3</td>
</tr>
<tr>
<td>Magnetizing reactance [Ohms]</td>
<td>137.5</td>
</tr>
<tr>
<td>Core loss component $R_{Fe}$ [Ohms]</td>
<td>2938</td>
</tr>
</tbody>
</table>
TABLE III: DATA OF BEARING FOR MOTOR SZJKE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers of balls Nb [-]</td>
<td>7</td>
</tr>
<tr>
<td>Ball diameter Bd [mm]</td>
<td>6</td>
</tr>
<tr>
<td>Bearing pitch diameter Pd [mm]</td>
<td>32</td>
</tr>
<tr>
<td>Contact angle $\alpha$ [rad]</td>
<td>0</td>
</tr>
</tbody>
</table>

B. Experiments

Three runs of experiments were performed on the healthy and shorted stator motors by varying the loads. The specifications of the experiments in terms of the load current, motor slip and the average rotor speed are shown in Table IV. It was tried to keep the three loading conditions (in terms of load current, slip and rotor speed) identical as much as possible for the healthy and the shorted stator cases. However, minor experimental variations could not be avoided. Nevertheless, these do not affect the diagnostic result.

C. Analysis

After the acquisition of the stator current samples at 10 kHz sampling frequency, for 10 seconds in each case, the ZCT signal was calculated from the current samples, as explained in section III.A. Then, a 999 point FFT [17] (as we have 1000 ZCT points) was used on the ZCT signal to calculate the frequency spectrum. The stator short circuit indicative frequency components are calculated using (10), based on the operating slip, and considering the fact that the machines have 2 pole pairs, connected to 50 Hz supply. The stator short circuit indicative frequency components are calculated in Table V, for $n=1,2,3$. We plot the frequency spectrums of the ZCT signals in the healthy and the shorted stator cases in Figs. 5–10.

TABLE IV: EXPERIMENTAL CONDITIONS FOR THE STATOR SHORT CIRCUIT DIAGNOSTICS

<table>
<thead>
<tr>
<th>Case</th>
<th>Nominal current (A)</th>
<th>Load current (A)</th>
<th>Slip value</th>
<th>Average rotor speed (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy1</td>
<td>2.2</td>
<td>1.81</td>
<td>0.037</td>
<td>1444.23</td>
</tr>
<tr>
<td>Healthy2</td>
<td>2.2</td>
<td>2.02</td>
<td>0.047</td>
<td>1429.36</td>
</tr>
<tr>
<td>Healthy3</td>
<td>2.2</td>
<td>2.25</td>
<td>0.058</td>
<td>1413.27</td>
</tr>
<tr>
<td>Short1</td>
<td>2.2</td>
<td>1.83</td>
<td>0.032</td>
<td>1450.91</td>
</tr>
<tr>
<td>Short2</td>
<td>2.2</td>
<td>2.02</td>
<td>0.042</td>
<td>1436.59</td>
</tr>
<tr>
<td>Short3</td>
<td>2.2</td>
<td>2.20</td>
<td>0.051</td>
<td>1422.68</td>
</tr>
</tbody>
</table>
TABLE V: Stator short indicative frequency component for different experiment cases, supply frequency $f_i = 50$ Hz, pole pairs $p = 2$

<table>
<thead>
<tr>
<th>Case</th>
<th>Slip value</th>
<th>$f_{smp}f_i(1 - \omega) / n / p$, $n = 1$ (Hz)</th>
<th>$f_{smp}f_i(1 - \omega) / n / p$, $n = 2$ (Hz)</th>
<th>$f_{smp}f_i(1 - \omega) / n / p$, $n = 3$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy1</td>
<td>0.037</td>
<td>24.075</td>
<td>48.15</td>
<td>72.225</td>
</tr>
<tr>
<td>Healthy2</td>
<td>0.047</td>
<td>23.825</td>
<td>47.65</td>
<td>71.475</td>
</tr>
<tr>
<td>Healthy3</td>
<td>0.058</td>
<td>23.55</td>
<td>47.1</td>
<td>70.65</td>
</tr>
<tr>
<td>Short1</td>
<td>0.032</td>
<td>24.2</td>
<td>48.4</td>
<td>72.6</td>
</tr>
<tr>
<td>Short2</td>
<td>0.042</td>
<td>23.95</td>
<td>47.9</td>
<td>71.85</td>
</tr>
<tr>
<td>Short3</td>
<td>0.051</td>
<td>23.725</td>
<td>47.45</td>
<td>71.175</td>
</tr>
</tbody>
</table>

Fig. 5. Frequency spectrum of the ZCT signal for the Healthy1 case.

Fig. 6. Frequency spectrum of the ZCT signal for the Healthy2 case.
Fig. 7. Frequency spectrum of the ZCT signal for the Healthy3 case.

Fig. 8. Frequency spectrum of the ZCT signal for the shorted stator (Short1) case.

Fig. 9. Frequency spectrum of the ZCT signal for the shorted stator (Short2) case.
From Table V and Figs. 5–10, we see that for the healthy cases (Figs. 5–7), we only see the presence of the rotor frequency in the ZCT spectrum, corresponding to \( n = 1 \) case (column 3 in Table V). The stator short indicative frequency components for \( n = 2, 3 \) (columns 4, 5 in Table V) are absent for the healthy cases, while those frequency peaks are predominantly present in the stator short cases, in Figs. 8–10, with an amplitude level of 20–30 dB, with respect to all noise levels considered as 0 dB. Also, in healthy cases, the rotor frequency has an amplitude level of about 20 dB, while for the stator short cases, the rotor frequency amplitude level is about 40 dB. This is because for the shorted stator cases, the additional stator short indicative frequency component (for \( n = 1 \)) coincide with the rotor frequency, increasing the overall magnitude level.

The small discrepancies in the frequency peak values in Figs. 5–10 compared to the estimated ones in Table V is due to the frequency resolution, influenced by the FFT window length. However, we can notice the deviations in the frequency peak values in Figs. 5–10 and the calculations in Table V are negligible. Therefore, the application results substantiate the theoretical arguments and the proposed stator short circuit detection algorithm using the frequency analysis of the ZCT signal, revealing the stator short indicative frequency peaks.

**D. Discussion of Results**

The following discussions can be cited on the application result.

i. All the tests were performed using real experimental recordings, as described in section IV.A. Frequency analysis of the ZCT signal was performed using the MATLAB® signal processing toolbox [18].

ii. The proposed algorithm can successfully distinguish between a healthy motor and one with shorted stator coils, by locating certain frequency peaks in the frequency spectrum of the ZCT signal.

iii. For the tests, it was ensured that the motors are completely healthy or had only stator short problem. No mixture of other faults like broken rotor bars, bearing problems, shaft misalignment, etc were included.

iv. Three-phase ZCT signal is used so that up to 150 Hz (for a 50 Hz supply) frequency range can be covered. This is needed as we have seen in the results section that we detect some frequency peaks in the range of 70 Hz (> 50 Hz). Hence, we cannot use single phase ZCT signal, as that would only cover up to 50 Hz frequency range.

v. The detection algorithm is not dependent on the supply frequency. That is, it would also work...
for other supply frequency, e.g. 60 Hz supply. In that case, the stator short indicative frequency peaks would differ. That can be easily calculated by changing the supply frequency \((f_s)\) in (10), and then updating Tables IV & V.

vi. From the traditional MCSA side, the frequency peak detection in the spectrum of the stator current also works. We show for the cases Healthy2 and Short2 in Figs. 11–12 respectively. It is to be noted from Table V, column 3, that for the cases, Healthy2 and Short2, the stator short indicative frequency peak for \(n=1\) are 23.825 Hz and 23.95 Hz respectively. As in Figs. 11–12 the stator short indicative peaks are shown for the spectrum of stator current, then as per (9), these peaks appear around the fundamental 50 Hz peak. Therefore, from (9), for \(n=1\) (this also gives the rotor frequency), and considering the positive sign, the peaks should be at 50+23.825=73.825 Hz and 50+23.95=73.95 Hz for the Healthy2 and the Short2 cases respectively. The peak at Fig. 11 is due to rotor frequency. For higher \(n=2,3,...\), we see that there are significant side peaks in case of stator short circuit (Fig. 12), while no such peak is present for the healthy motor (Fig. 11). From (9), if we consider the negative sign, then we expect to see peaks on the left side of the fundamental peak. Therefore, for \(n=1\), considering the negative sign in (9), the peaks should be at 50–23.825= 26.175 Hz and 50–23.95=26.05 Hz for the Healthy2 and the Short2 cases respectively. These are also visible in Figs. 11 and 12 (marked in square). And as expected, the magnitude of this peak is about twice (60 dB) in the stator short case than the healthy case (30 dB). For \(n>1\), this peak would be close to 0 or negative, hence there would be no significance with respect to stator short indication. We also see that, setting \(k=3.5\) and \(n=1\) in (9), we see side peaks at about
\[
3 \times 50 + 23.95 = 173.95 \text{ Hz and } 5 \times 50 + 23.95 = 273.95 \text{ Hz in Fig. 12.}
\]

vii. We have used the value of the parameter \(k=1\) for the analysis of the ZCT signal. This is because, from (9 & 10), we see that the alteration of the air gap flux due to the stator short circuit is only caused by the frequency component in (10) which is not dependent on \(k\). Besides, choosing a value of \(k=3.5,...>1\) would imply looking for the frequency peaks (in the spectrum of stator current not ZCT) around higher harmonics of the fundamental peak. The fundamental peak corresponds to \(k=1\), and higher harmonics for \(k=3.5,...>1\). Therefore, the choice of \(k\) is non-influential for the ZCT signal-based detection of shorted stator winding.

viii. As discussed before, utilization of the ZCT signal reduces the number of samples, hence computational burden. This is an alternative approach to the MCSA using the stator current. This approach is particularly helpful for lower end devices with limited computational power, e.g., without DSPs, with less memory and storage, etc.
E. Future Directions

i. For this work, we utilized a motor with 50% shorted stator (50% short does not mean 50% of the total number of coils were shorted, but 50% indicates that the voltage across the shorted coils attain 50% of the per phase voltage). With the promising ZCT signal-based stator short detection results, we further plan to test and detect different levels of voltage across shorted coils. For random wound windings, it is chance dependent, as different contiguous windings might be electrically apart, causing different voltage drops. However, it is important to check high voltage values (e.g., 50% in our cases is a good example) as that might cause higher short-circuit currents. A voltmeter can be used to check the voltage across the shorted coils.

ii. We also plan to test and detect development of serious short circuit problems between two or more phases, starting from a single-phase interturn short circuit fault. This would be helpful to identify the critical transition time between development of a small interturn short circuit till serious fault and motor breakdown. There could be different trend depending on the power rating of the motor.

iii. From the processing side, we would compare different window length of FFT. In this work, we utilized about 1000-point FFT. We plan to check and compare how low we can go with the window and frequency resolution. This would be helpful for real-time implementations.
iv. Following the promising results, we would also test how uncertainties in experimental conditions like offsets in ZCT measurement (specially for direct hardware measurements of ZCT), etc might affect the detection accuracy in all the abovementioned conditions and different levels of short circuit.

V. CONCLUSIONS

We have presented in this paper the application of the ZCT signal for the detection of stator short circuit fault in three-phase induction motors. The theoretical aspects of the stator short circuit detection was presented. As indicated by previous studies [9–12], due to short circuits in the stator windings, the air gap flux distribution is altered. This will induce an emf in the shorted turn which will result in a current flow limited only by the self impedance of the fault. The corresponding frequency peaks, \( f_{\text{comp}} = \frac{n}{p} \left( \frac{1}{s} \right) \), will appear in the ZCT spectrum. These peaks will depend on the supply frequency, number of pole pairs, slip and a parameter \( n = 1,2,3,\ldots \). The frequency peak for \( n = 1 \) will coincide with the rotor frequency. Experiments were performed on real motors, healthy and with shorted stator windings. Frequency analysis of the ZCT signals from the experimental data substantiate the theoretical arguments, revealing the existence of the stator short indicative frequency peaks for the faulty motor, with no such peaks in case of healthy one. The accuracy of the stator short indicative frequency peak locations in the experimental data in comparison to the theoretical estimates is quite significant.

The traditional MCSA-based diagnostics using the spectrum of the stator current also reveals the existence of such indicative peaks. However, this paper presents an alternative approach using the ZCT signal. Usage of ZCT signal instead of stator current would be beneficial in terms of cheaper computational burden and so forth. This would also not require any additional sensor, but the ZCT signal could be easily calculated from the measured stator current (described in the paper), or directly measured with some additional electronics (in many cases available). This will be an effective approach if we have no or only partial current measurement, e.g., rectified current, peak current measurement, etc available. The ZCT-based approach would work for any supply frequency, as the location of the stator short indicative frequencies would change depending on the supply frequency, which can be calculated from the abovementioned theoretical relations and then looked at the ZCT spectrum.

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REFERENCES

264, 1983.
circuits in the stator windings of operating motors,” IEEE Trans. Energy Conversion, vol. 9,
2001
of three-phase induction motors prior to failure,” in proc. IEEE PES & IAS IEMDC, Boston,
fluctuations of motor current zero crossing instants,” Electric Power Systems Research,
2008.
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FIGURE & TABLE CAPTIONS

Fig. 1. Schematic diagram of different stator short possibilities.
Fig. 2. Calculation of ZC times from a single phase stator current.
Fig. 3. Flowchart of the stator short circuit detection algorithm using the ZCT signal.
Fig. 4. (a) The laboratory setup for induction motor stator short circuit experiments, (b) the random wound stator winding of the motor types used in the experiments.
Fig. 5. Frequency spectrum of the ZCT signal for the Healthy1 case.
Fig. 6. Frequency spectrum of the ZCT signal for the Healthy2 case.
Fig. 7. Frequency spectrum of the ZCT signal for the Healthy3 case.
Fig. 8. Frequency spectrum of the ZCT signal for the shorted stator (Short1) case.
Fig. 9. Frequency spectrum of the ZCT signal for the shorted stator (Short2) case.
Fig. 10. Frequency spectrum of the ZCT signal for the shorted stator (Short3) case.
Fig. 11. Frequency spectrum of the stator current signal for the Healthy2 case.
Fig. 12. Frequency spectrum of the stator current signal for the shorted stator (Short2) case.

TABLE I: Ratings of motor SZJKe
TABLE II: Equivalent circuit parameters of motor SZJKe
TABLE III: Data of bearing for motor SZJKe
TABLE IV: Experimental conditions for the stator short circuit diagnostics
TABLE V: Stator short indicative frequency component for different experiment cases, supply frequency $f_i = 50$ Hz, pole pairs $p = 2$